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Grounding and Lightning¹

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12.1 Lightning Stroke Protection

Substation design involves more than installing apparatus, protective devices, and equipment. The significant monetary investment and required reliable continuous operation of the facility requires detailed attention to preventing surges (transients) from entering the substation facility. These surges can be switching surges, lightning surges on connected transmission lines, or direct strokes to the substation facility. The origin and mechanics of these surges, including lightning, are discussed in detail in [Chapter 10](#) of *The Electric Power Engineering Handbook* (CRC Press, 2001). This section focuses on the design process for providing *effective shielding* (that which permits lightning strokes no greater than those of critical amplitude [less design margin] to reach phase conductors [IEEE Std. 998-1996]) against direct lightning stroke in substations.

¹A large portion of the text and all of the figures used in the following discussion were prepared by the Direct Stroke Shielding of Substations Working Group of the Substations Committee — IEEE Power Engineering Society, and published as IEEE Std. 998-1996, *IEEE Guide for Direct Lightning Stroke Shielding of Substations*, Institute of Electrical and Electronics Engineers, Inc., 1996. The IEEE disclaims any responsibility or liability resulting from the placement or use in the described manner. Information is reprinted with the permission of the IEEE. The author has been a member of the working group since 1987.

12.1.1 The Design Problem

The engineer who seeks to design a direct stroke shielding system for a substation or facility must contend with several elusive factors inherent in lightning phenomena, namely:

- The unpredictable, probabilistic nature of lightning
- The lack of data due to the infrequency of lightning strokes in substations
- The complexity and economics involved in analyzing a system in detail

There is no known method of providing 100% shielding short of enclosing the equipment in a solid metallic enclosure. The uncertainty, complexity, and cost of performing a detailed analysis of a shielding system has historically resulted in simple rules of thumb being utilized in the design of lower voltage facilities. Extra high voltage (EHV) facilities, with their critical and more costly equipment components, usually justify a more sophisticated study to establish the risk vs. cost benefit.

Because of the above factors, it is suggested that a four-step approach be utilized in the design of a protection system:

1. Evaluate the importance and value of the facility being protected.
2. Investigate the severity and frequency of thunderstorms in the area of the substation facility and the exposure of the substation.
3. Select an appropriate design method consistent with the above evaluation and then lay out an appropriate system of protection.
4. Evaluate the effectiveness and cost of the resulting design.

The following paragraphs and references will assist the engineer in performing these steps.

12.2 Lightning Parameters

12.2.1 Strike Distance

Return stroke current magnitude and strike distance (length of the last stepped leader) are interrelated. A number of equations have been proposed for determining the striking distance. The principal ones are as follows:

$$S = 2I + 30 \left(1 - e^{-I/6.8} \right) \quad \text{Darveniza (1975)} \quad (12.1)$$

$$S = 10 I^{0.65} \quad \text{Love (1987; 1993)} \quad (12.2)$$

$$S = 9.4 I^{2/3} \quad \text{Whitehead (1974)} \quad (12.3)$$

$$S = 8 I^{0.65} \quad \text{IEEE (1985)} \quad (12.4)$$

$$S = 3.3 I^{0.78} \quad \text{Suzuki (1981)} \quad (12.5)$$

where

S is the strike distance in meters

I is the return stroke current in kiloamperes

It may be disconcerting to note that the above equations vary by as much as a factor of 2:1. However, lightning investigators now tend to favor the shorter strike distances given by Equation 12.4. Anderson, for example, who adopted Equation 12.2 in the 1975 edition of the *Transmission Line Reference Book* (1987), now feels that Equation 12.4 is more accurate. Mousa (1988) also supports this form of the equation. The equation may also be stated as follows:

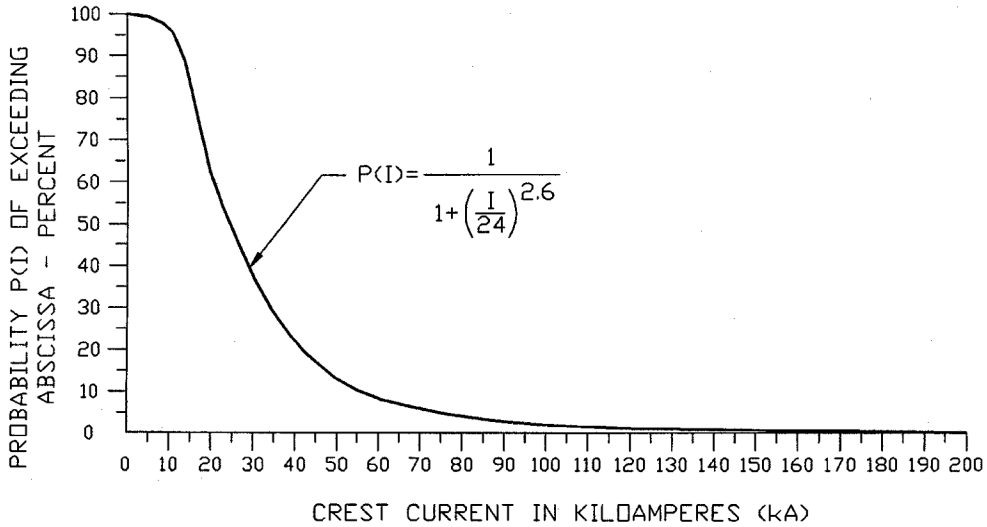


FIGURE 12.1 Probability of stroke current exceeding abscissa for strokes to flat ground. (IEEE Std. 998-1996. With permission.)

$$I = 0.041 S^{1.54} \quad (12.6)$$

From this point on, the return stroke current will be referenced as the *stroke current*.

12.2.2 Stroke Current Magnitude

Since the stroke current and striking distance are related, it is of interest to know the distribution of stroke current magnitudes. The median value of strokes to OHGW, conductors, structures, and masts is usually taken to be 31 kA (Anderson, 1987). Anderson (1987) gave the probability that a certain peak current will be exceeded in any stroke as follows:

$$P(I) = 1 / \left[1 + \left(I/31 \right)^{2.6} \right] \quad (12.7)$$

where

$P(I)$ is the probability that the peak current in any stroke will exceed I
 I is the specified crest current of the stroke in kiloamperes

Mousa (1989) has shown that a median stroke current of 24 kA for strokes to flat ground produces the best correlation with available field observations to date. Using this median value of stroke current, the probability that a certain peak current will be exceeded in any stroke is given by the following equation:

$$P(I) = 1 / \left[1 + \left(I/24 \right)^{2.6} \right] \quad (12.8)$$

where the symbols have the same meaning as above.

Figure 12.1 is a plot of Equation 12.8, and Figure 12.2 is a plot of the probability that a stroke will be within the ranges shown on the abscissa.



FIGURE 12.2 Stroke current range probability for strokes to flat ground. (IEEE Std. 998-1996. With permission.)

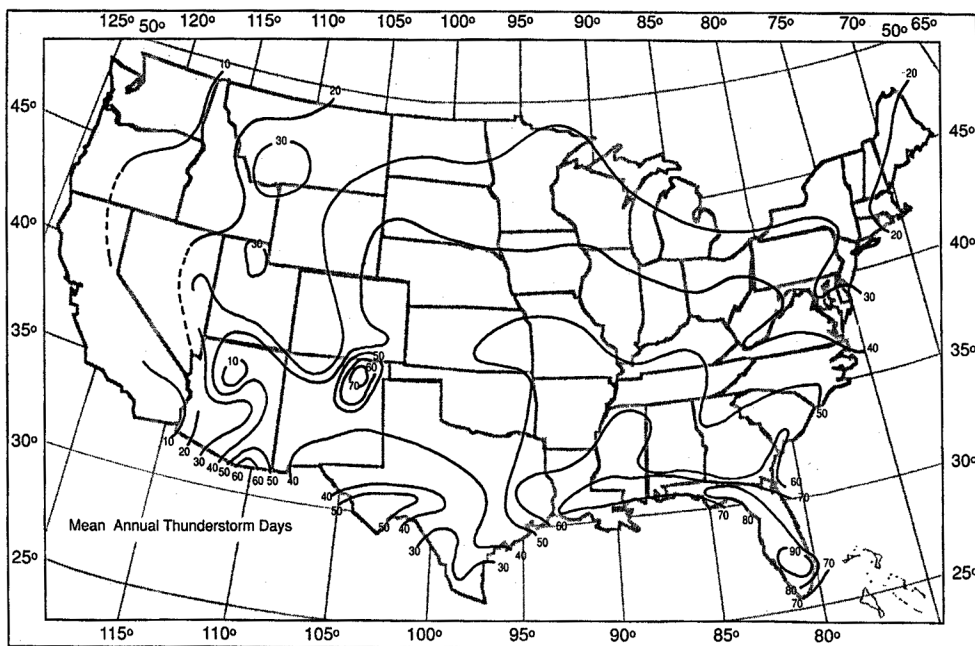


FIGURE 12.3 Mean annual thunderstorm days in the U.S. (IEEE Std. 998-1996. With permission.)

12.2.3 Keraunic Level

Keraunic level is defined as the average annual number of thunderstorm days or hours for a given locality. A daily keraunic level is called a thunderstorm-day and is the average number of days per year on which thunder will be heard during a 24-h period. By this definition, it makes no difference how many times thunder is heard during a 24-h period. In other words, if thunder is heard on any one day more than one time, the day is still classified as one thunder-day (or thunderstorm day). The average annual keraunic level for locations in the U.S. can be determined by referring to isokeraunic maps on which lines of equal keraunic level are plotted on a map of the country. Figure 12.3 gives the mean annual thunderstorm days for the U.S.

12.2.4 Ground Flash Density

Ground flash density (GFD) is defined as the average number of strokes per unit area per unit time at a particular location. It is usually assumed that the GFD to earth, a substation, or a transmission or distribution line is roughly proportional to the keraunic level at the locality. If thunderstorm days are to be used as a basis, it is suggested that the following equation be used (Anderson, 1987):

$$N_k = 0.12 T_d \quad (12.9)$$

or

$$N_m = 0.31 T_d \quad (12.10)$$

where

N_k is the number of flashes to earth per square kilometer per year

N_m is the number of flashes to earth per square mile per year

T_d is the average annual keraunic level, thunderstorm days

12.2.5 Lightning Detection Networks

A new technology is now being deployed in Canada and the U.S. that promises to provide more accurate information about ground flash density and lightning stroke characteristics. Mapping of lightning flashes to the earth has been in progress for over a decade in Europe, Africa, Australia, and Asia. Now a network of direction-finding receiving stations has been installed across Canada and the U.S. By means of triangulation among the stations, and with computer processing of signals, it is possible to pinpoint the location of each lightning discharge. Hundreds of millions of strokes have been detected and plotted to date.

Ground flash density maps have already been prepared from this data, but with the variability in frequency and paths taken by thunderstorms from year to year, it will take a number of years to develop data that is statistically significant. Some electric utilities are, however, taking advantage of this technology to detect the approach of thunderstorms and to plot the location of strikes on their system. This information is very useful for dispatching crews to trouble spots and can result in shorter outages that result from lightning strikes.

12.3 Empirical Design Methods

Two classical design methods have historically been employed to protect substations from direct lightning strokes:

1. Fixed angles
2. Empirical curves

The two methods have generally provided acceptable protection.

12.3.1 Fixed Angles

The fixed-angle design method uses vertical angles to determine the number, position, and height of shielding wires or masts. [Figure 12.4](#) illustrates the method for shielding wires, and [Figure 12.5](#) illustrates the method for shielding masts. The angles used are determined by the degree of lightning exposure, the importance of the substation being protected, and the physical area occupied by the substation. The value of the angle alpha that is commonly used is 45°. Both 30° and 45° are widely used for angle beta. (Sample calculations for low-voltage and high-voltage substations using fixed angles are given in annex B of IEEE Std. 998-1996.)

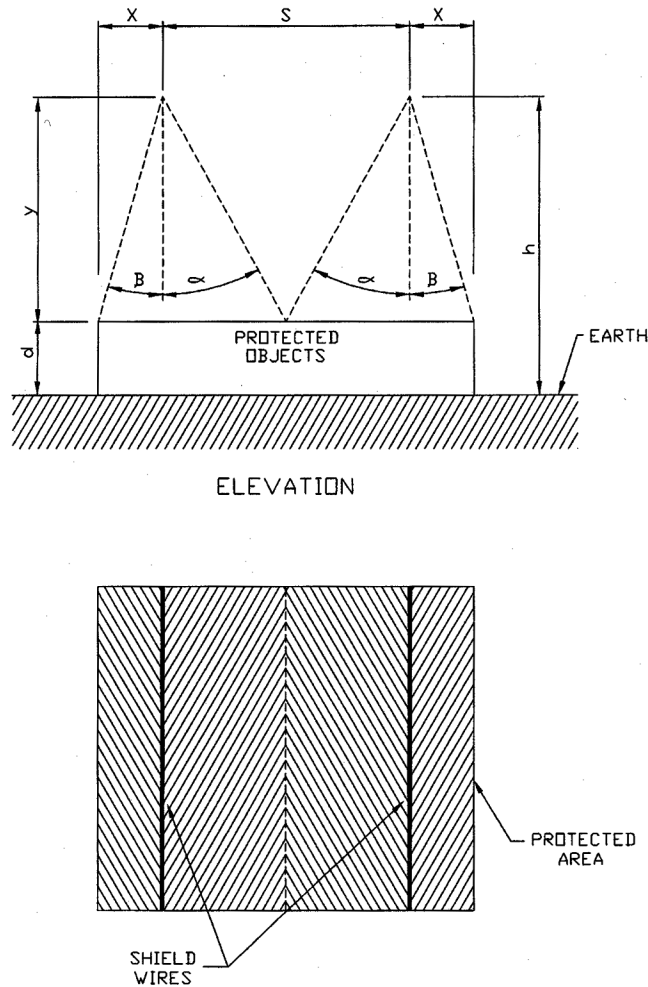


FIGURE 12.4 Fixed angles for shielding wires. (IEEE Std. 998-1996. With permission.)

12.3.2 Empirical Curves

From field studies of lightning and laboratory model tests, empirical curves have been developed to determine the number, position, and height of shielding wires and masts (Wagner et al., 1941; Wagner, 1942; Wagner, McCann, Beck, 1941). The curves were developed for shielding failure rates of 0.1, 1.0, 5.0, 10, and 15%. A failure rate of 0.1% is commonly used in design. Figure 12.6 and Figure 12.7 have been developed for a variety of protected object heights, d . The empirical curve method has also been referred to as the Wagner method.

12.3.2.1 Areas Protected by Lightning Masts

Figure 12.8 and Figure 12.9 illustrate the areas that can be protected by two or more shielding masts (Wagner et al., 1942). If two masts are used to protect an area, the data derived from the empirical curves give shielding information only for the point B , midway between the two masts, and for points on the semicircles drawn about the masts, with radius x , as shown in Figure 12.8a. The locus shown in Figure 12.8a, drawn by the semicircles around the masts, with radius x , and connecting the point B , represents an approximate limit for a selected exposure rate. Any single point falling within the cross-hatched area should have $<0.1\%$ exposure. Points outside the cross-hatched area will have $>0.1\%$ exposure. Figure 12.8b illustrates this phenomenon for four masts spaced at the distance s as in Figure 12.8a.

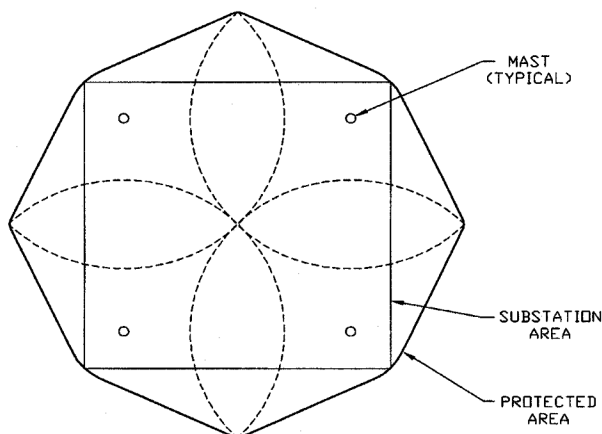
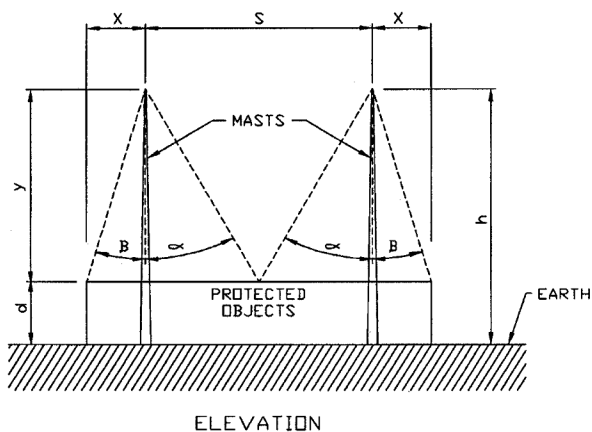


FIGURE 12.5 Fixed angles for masts. (IEEE Std. 998-1996. With permission.)

The protected area can be improved by moving the masts closer together, as illustrated in Figure 12.9. In Figure 12.9a, the protected areas are, at least, as good as the combined areas obtained by superimposing those of Figure 12.8a. In Figure 12.9a, the distance s' is one half the distance s in Figure 12.8a. To estimate the width of the overlap, x' , first obtain a value of y corresponding to twice the distance s' between the masts. Then use Figure 12.6 to determine x' for this value of y . This value of x is used as an estimate of the width of overlap x' in Figure 12.9. As illustrated in Figure 12.9b, the size of the areas with an exposure greater than 0.1% has been significantly reduced. (Sample calculations for low-voltage and high-voltage substations using empirical curves are given in annex B of IEEE Std. 998-1996.)

12.4 The Electrometric Model (EGM)

Shielding systems developed using classical methods (fixed angles and empirical curves) of determining the necessary shielding for direct stroke protection of substations have historically provided a fair degree of protection. However, as voltage levels (and therefore structure and conductor heights) have increased over the years, the classical methods of shielding design have proven less adequate. This led to the development of the electrometric model.

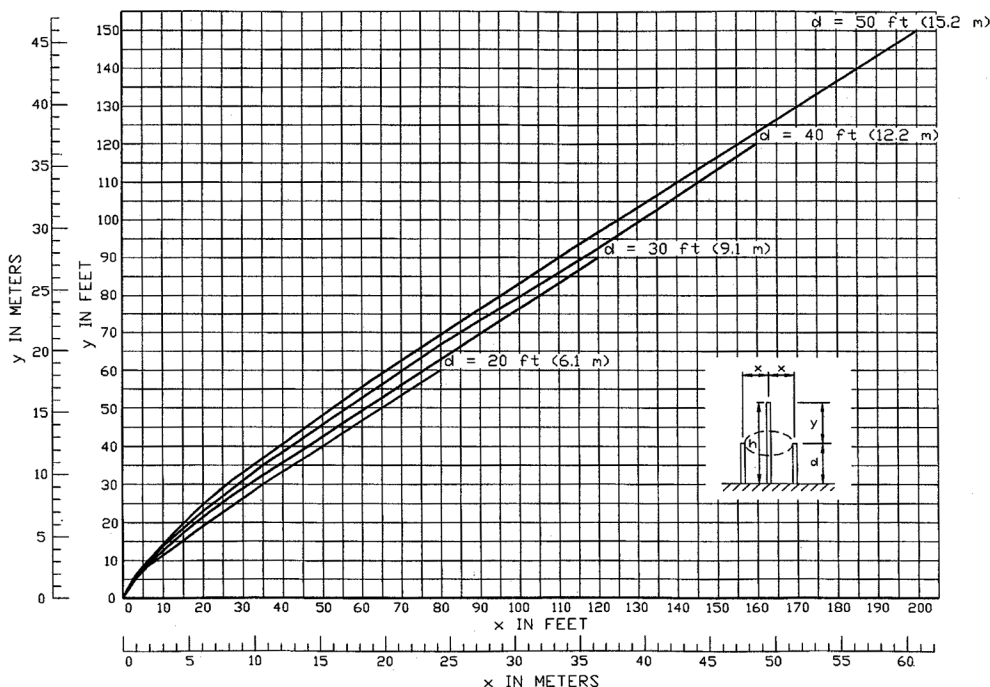


FIGURE 12.6 Single lightning mast protecting single ring of object — 0.1% exposure. Height of mast above protected object, y , as a function of horizontal separation, x , and height of protected object, d . (IEEE Std. 998-1996. With permission.)

12.4.1 Whitehead's EGM

In 1960, Anderson developed a computer program for calculation of transmission line lightning performance that uses the *Monte Carlo Method* (1961). This method showed good correlation with actual line performance. An early version of the EGM was developed in 1963 by Young et al., but continuing research soon led to new models. One extremely significant research project was performed by Whitehead (1971). Whitehead's work included a theoretical model of a transmission system subject to direct strokes, development of analytical expressions pertaining to performance of the line, and supporting field data that verified the theoretical model and analyses. The final version of this model was published by Gilman and Whitehead in 1973.

12.4.2 Recent Improvements in the EGM

Sargent made an important contribution with the *Monte Carlo Simulation* of lightning performance (1972) and his work on lightning strokes to tall structures (1972). Sargent showed that the frequency distribution of the amplitudes of strokes collected by a structure depends on the structure height as well as on its type (mast vs. wire). In 1976, Mousa extended the application of the EGM (which was developed for transmission lines) to substation facilities.

12.4.3 Criticism of the EGM

Work by Eriksson reported in 1978 and later work by Anderson and Eriksson reported in 1980 revealed apparent discrepancies in the EGM that tended to discredit it. Mousa (1988) has shown, however, that explanations do exist for the apparent discrepancies, and that many of them can be eliminated by adopting a revised electrogeometric model. Most investigators now accept the EGM as a valid approach for designing lightning shielding systems.

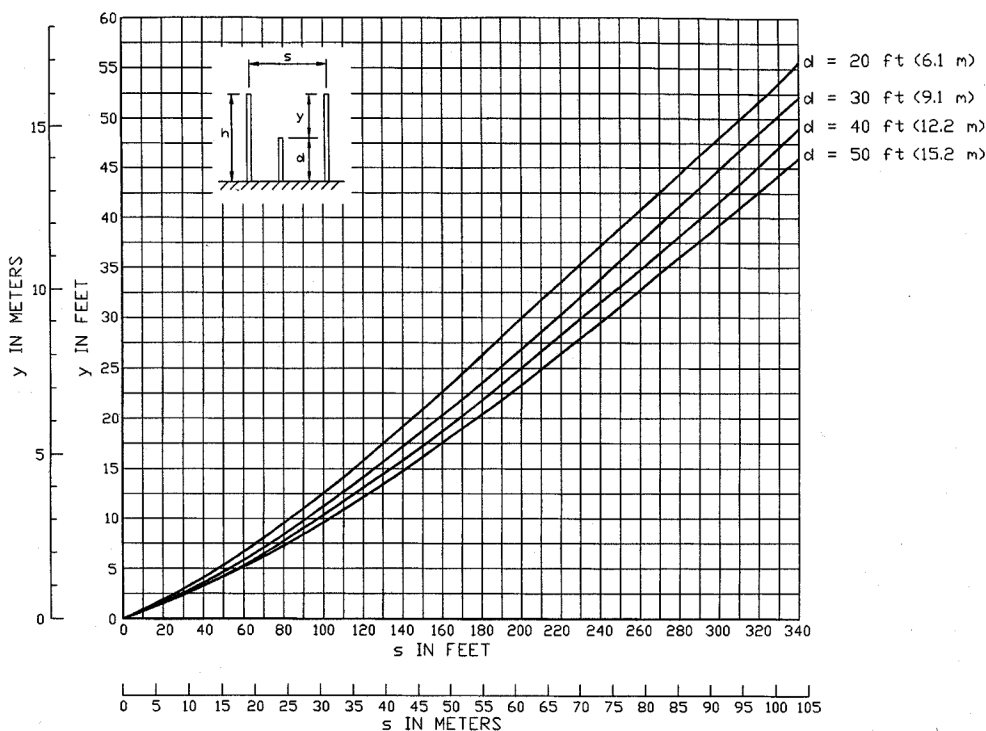


FIGURE 12.7 Two lightning masts protecting single object, no overlap — 0.1% exposure. Height of mast above protected object, y , as a function of horizontal separation, s , and height of protected object, d . (IEEE Std. 998-1996. With permission.)

12.4.4 A Revised EGM

The revised EGM was developed by Mousa and Srivastava (1986; 1988). Two methods of applying the EGM are the modified version of the rolling sphere method (Lee, 1979; Lee, 1978; Orell, 1988), and the method given by Mousa and Srivastava (1988; 1991).

The revised EGM model differs from Whitehead's model in the following respects:

1. The stroke is assumed to arrive in a vertical direction. (It has been found that Whitehead's assumption of the stroke arriving at random angles is an unnecessary complication [Mousa and Srivastava, 1988].)
2. The differing striking distances to masts, wires, and the ground plane are taken into consideration.
3. A value of 24 kA is used as the median stroke current (Mousa and Srivastava, 1989). This selection is based on the frequency distribution of the first negative stroke to flat ground. This value best reconciles the EGM with field observations.
4. The model is not tied to a specific form of the striking distance equations (Equation 12.1 through Equation 12.6). Continued research is likely to result in further modification of this equation as it has in the past. The best available estimate of this parameter may be used.

12.4.4.1 Description of the Revised EGM

Previously, the concept that the final striking distance is related to the magnitude of the stroke current was introduced and Equation 12.4 was selected as the best approximation of this relationship. A coefficient k accounts for the different striking distances to a mast, a shield wire, and to the ground. Equation 12.4 is repeated here with this modification:

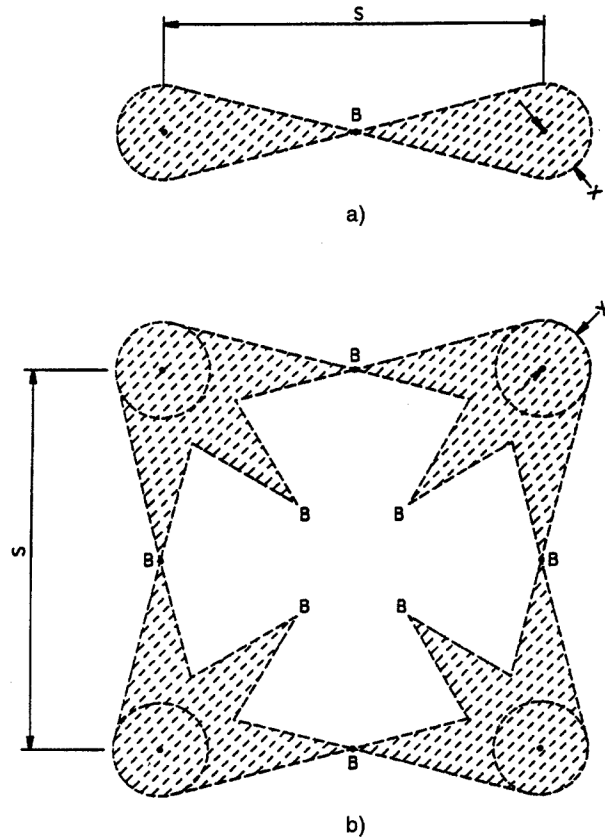


FIGURE 12.8 Areas protected by multiple masts for point exposures shown in Figure 12.5a with two lightning masts, 12.5b with four lightning masts. (IEEE Std. 998-1996. With permission.)

$$S_m = 8kI^{0.65} \quad (12.11)$$

or

$$S_f = 26.25kI^{0.65} \quad (12.12)$$

where

S_m is the strike distance in meters

S_f is the strike distance in feet

I is the return stroke current in kiloamperes

k is a coefficient to account for different striking distances to a mast, a shield wire, or the ground plane

Mousa (1988) gives a value of $k = 1$ for strokes to wires or the ground plane and a value of $k = 1.2$ for strokes to a lightning mast.

Lightning strokes have a wide distribution of current magnitudes, as shown in Figure 12.1. The EGM theory shows that the protective area of a shield wire or mast depends on the amplitude of the stroke current. If a shield wire protects a conductor for a stroke current I_s , it may not shield the conductor for a stroke current less than I_s that has a shorter striking distance. Conversely, the same shielding arrangement will provide greater protection against stroke currents greater than I_s that have greater striking distances.

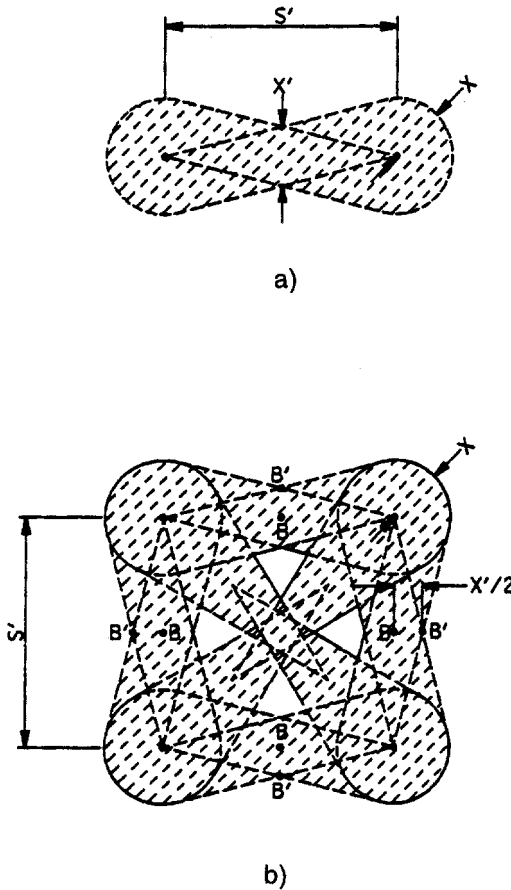


FIGURE 12.9 Areas protected by multiple masts for point exposures shown in Figure 12.5 (a) With two lightning masts; (b) with four lightning masts. (IEEE Std. 998-1996. With permission.)

Since strokes less than some critical value I_s can penetrate the shield system and terminate on the protected conductor, the insulation system must be able to withstand the resulting voltages without flashover. Stated another way, the shield system should intercept all strokes of magnitude I_s and greater so that flashover of the insulation will not occur.

12.4.4.2 Allowable Stroke Current

Some additional relationships need to be introduced before showing how the EGM is used to design a zone of protection for substation equipment. Bus insulators are usually selected to withstand a *basic lightning impulse level* (BIL). Insulators may also be chosen according to other electrical characteristics, including negative polarity *impulse critical flashover* (CFO) voltage. Flashover occurs if the voltage produced by the lightning stroke current flowing through the surge impedance of the station bus exceeds the withstand value. This may be expressed by the Gilman and Whitehead equation (1973):

$$I_s = \text{BIL} \times 1.1 / (Z_s / 2) = 2.2 (\text{BIL}) / Z_s \quad (12.13)$$

or

$$I_s = 0.94 \times \text{C.F.O.} \times 1.1 / (Z_s / 2) = 2.068 (\text{C.F.O.}) / Z_s \quad (12.14)$$

where

- I_s is the allowable stroke current in kiloamperes
- BIL is the basic lightning impulse level in kilovolts
- CFO is the negative polarity critical flashover voltage of the insulation being considered in kilovolts
- Z_s is the surge impedance of the conductor through which the surge is passing in ohms
- 1.1 is the factor to account for the reduction of stroke current terminating on a conductor as compared to zero impedance earth (Gilman and Whitehead, 1973)

In Equation 12.14, the CFO has been reduced by 6% to produce a withstand level roughly equivalent to the BIL rating for post insulators.

Withstand Voltage of Insulator Strings

BIL values of station post insulators can be found in vendor catalogs. A method is given below for calculating the withstand voltage of insulator strings. The withstand voltage in kV at 2 μ s and 6 μ s can be calculated as follows:

$$V_{I2} = 0.94 \times 820 w \quad (12.15)$$

$$V_{I6} = 0.94 \times 585 w \quad (12.16)$$

where

- w is the length of insulator string (or air gap) in meters
- 0.94 is the ratio of withstand voltage to CFO voltage
- V_{I2} is the withstand voltage in kilovolts at 2 μ s
- V_{I6} is the withstand voltage in kilovolts at 6 μ s

Equation 12.16 is recommended for use with the EGM.

12.4.5 Application of the EGM by the Rolling Sphere Method

It was previously stated that it is only necessary to provide shielding for the equipment from all lightning strokes greater than I_s that would result in a flashover of the buswork. Strokes less than I_s are permitted to enter the protected zone since the equipment can withstand voltages below its BIL design level. This will be illustrated by considering three levels of stroke current: I_s , stroke currents greater than I_s , and stroke currents less than I_s . First, let us consider the stroke current I_s .

12.4.5.1 Protection Against Stroke Current I_s

I_s is calculated from Equation 12.13 or Equation 12.14 as the current producing a voltage the insulation will just withstand. Substituting this result in Equation 12.11 or Equation 12.12 gives the striking distance S for this stroke current. In 1977, Lee developed a simplified technique for applying the electrogeometric theory to the shielding of buildings and industrial plants (1982; 1979; 1978). Orrell extended the technique to specifically cover the protection of electric substations (1988). The technique developed by Lee has come to be known as the rolling sphere method. For the following illustration, the *rolling sphere* method will be used. This method employs the simplifying assumption that the striking distances to the ground, a mast, or a wire are the same. With this exception, the rolling sphere method has been updated in accordance with the revised EGM.

Use of the rolling sphere method involves rolling an imaginary sphere of radius S over the surface of a substation. The sphere rolls up and over (and is supported by) lightning masts, shield wires, substation fences, and other grounded metallic objects that can provide lightning shielding. A piece of equipment is said to be protected from a direct stroke if it remains below the curved surface of the sphere by virtue

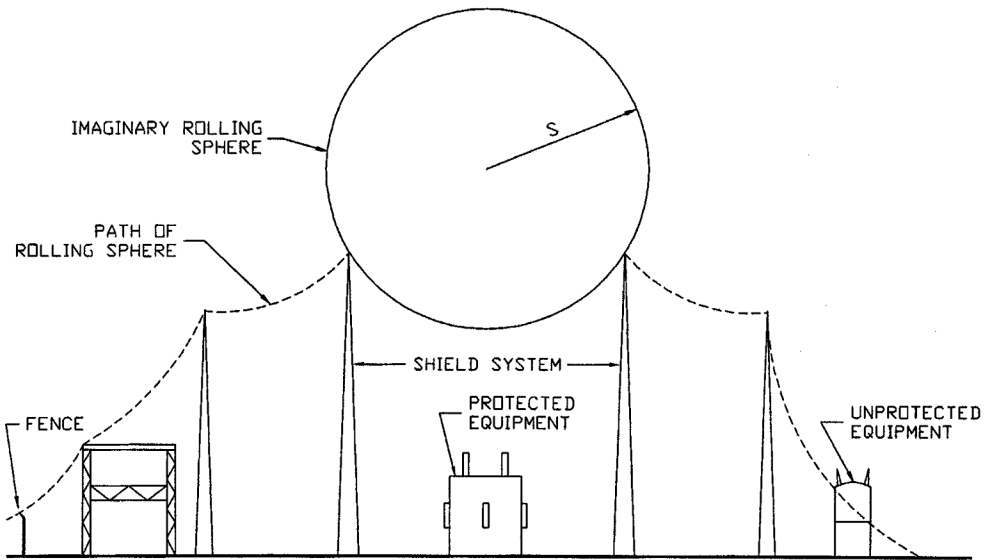


FIGURE 12.10 Principle of the rolling sphere. (IEEE Std. 998-1996. With permission.)

of the sphere being elevated by shield wires or other devices. Equipment that touches the sphere or penetrates its surface is not protected. The basic concept is illustrated in Figure 12.10.

Continuing the discussion of protection against stroke current I_s , consider first a single mast. The geometrical model of a single substation shield mast, the ground plane, the striking distance, and the zone of protection are shown in Figure 12.11. An arc of radius S that touches the shield mast and the ground plane is shown in Figure 12.11. All points below this arc are protected against the stroke current I_s . This is the protected zone. The arc is constructed as follows (see Figure 12.11). A dashed line is drawn parallel to the ground at a distance S (the striking distance as obtained from Equation 12.11 or Equation 12.12) above the ground plane. An arc of radius S , with its center located on the dashed line, is drawn so the radius of the arc just touches the mast. Stepped leaders that result in stroke current I_s and that descend outside of the point where the arc is tangent to the ground will strike the ground. Stepped leaders that result in stroke current I_s and that descend inside the point where the arc is tangent to the ground will strike the shield mast, provided all other objects are within the protected zone. The height of the shield mast that will provide the maximum zone of protection for stroke currents equal to I_s is S . If the mast height is less than S , the zone of protection will be reduced. *Increasing the shield mast height greater than S will provide additional protection in the case of a single mast. This is not necessarily true in the case of multiple masts and shield wires.* The protection zone can be visualized as the surface of a sphere with radius S that is rolled toward the mast until touching the mast. As the sphere is rolled around the mast, a three-dimensional surface of protection is defined. It is this concept that has led to the name *rolling sphere* for simplified applications of the electrogeometric model.

12.4.5.2 Protection Against Stroke Currents Greater than I_s

A lightning stroke current has an infinite number of possible magnitudes, however, and the substation designer will want to know if the system provides protection at other levels of stroke current magnitude. Consider a stroke current I_{s1} with magnitude greater than I_s . Strike distance, determined from Equation 12.11 or Equation 12.12, is $S1$. The geometrical model for this condition is shown in Figure 12.12. Arcs of protection for stroke current I_{s1} and for the previously discussed I_s are both shown. The figure shows that the zone of protection provided by the mast for stroke current I_{s1} is greater than the zone of protection provided by the mast for stroke current I_s . Stepped leaders that result in stroke current I_{s1} and that descend outside of the point where the arc is tangent to the ground will strike the

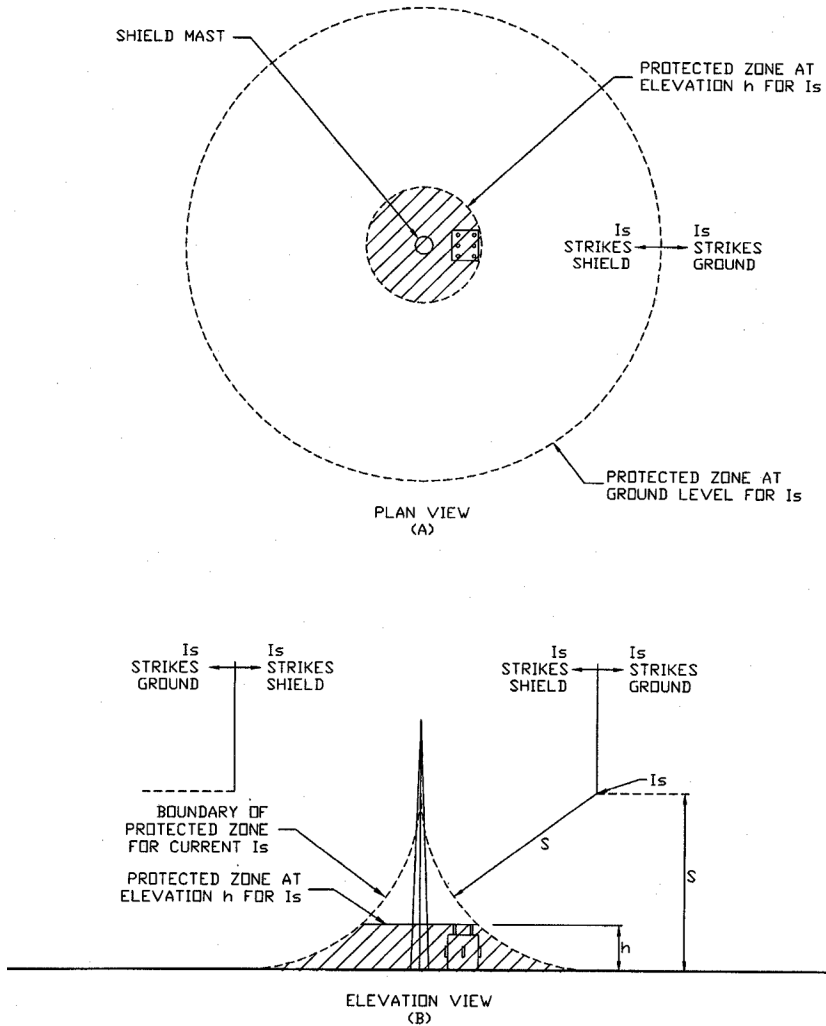


FIGURE 12.11 Shield mast protection for stroke current I_s . (IEEE Std. 998-1996. With permission.)

ground. Stepped leaders that result in stroke current I_{s1} and that descend inside the point where the arc is tangent to the ground will strike the shield mast, provided all other objects are within the S1 protected zone. Again, the protective zone can be visualized as the surface of a sphere touching the mast. In this case, the sphere has a radius $S1$.

12.4.5.3 Protection Against Stroke Currents Less than I_s

It has been shown that a shielding system that provides protection at the stroke current level I_s provides even better protection for larger stroke currents. The remaining scenario to examine is the protection afforded when stroke currents are less than I_s . Consider a stroke current I_{s0} with magnitude less than I_s . The striking distance, determined from Equation 12.11 or Equation 12.12, is S_0 . The geometrical model for this condition is shown in Figure 12.13. Arcs of protection for stroke current I_{s0} and I_s are both shown. The figure shows that the zone of protection provided by the mast for stroke current I_{s0} is less than the zone of protection provided by the mast for stroke current I_s . It is noted that a portion of the equipment protrudes above the dashed arc or zone of protection for stroke current I_{s0} . Stepped leaders that result in stroke current I_{s0} and that descend outside of the point where the arc is tangent to the ground will strike the ground. However, some stepped leaders that result in stroke current I_{s0} and that descend inside the point where the arc is tangent to the ground could strike the equipment. This is best shown by

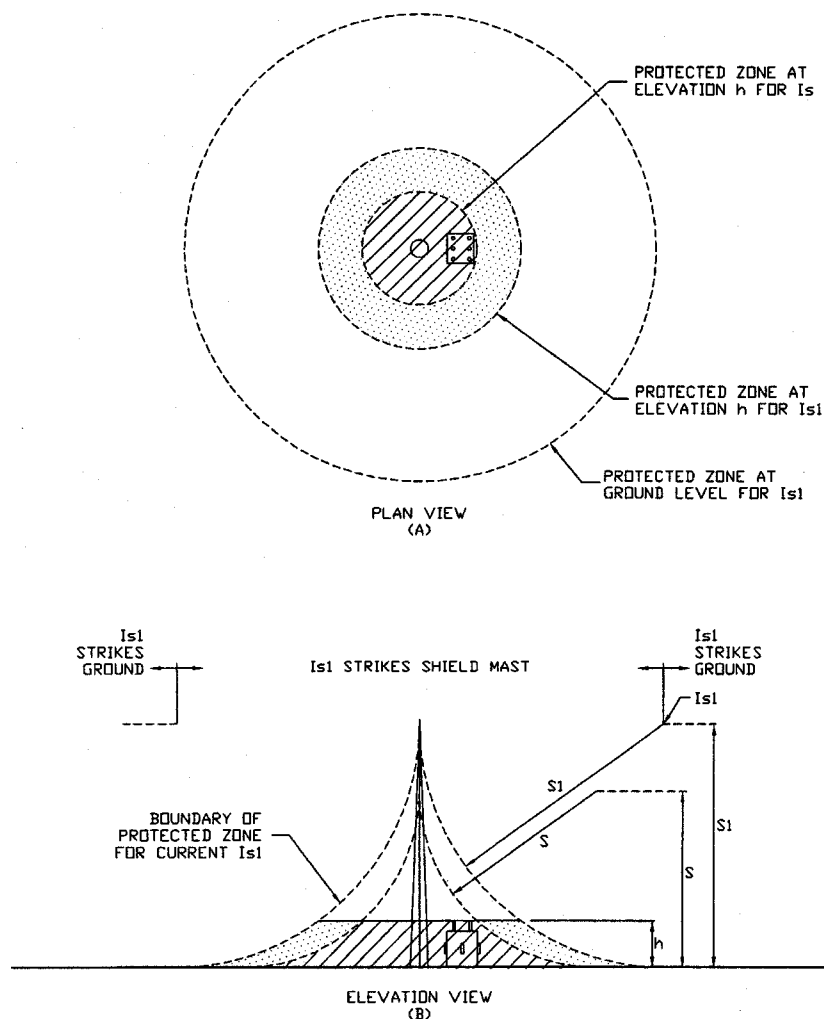


FIGURE 12.12 Shield mast protection for stroke current I_{s1} . (IEEE Std. 998-1996. With permission.)

observing the plan view of protective zones shown in Figure 12.13. Stepped leaders for stroke current I_{s0} that descend inside the inner protective zone will strike the mast and protect equipment that is h in height. Stepped leaders for stroke current I_{s0} that descend in the shaded unprotected zone will strike equipment of height h in the area. If, however, the value of I_s was selected based on the withstand insulation level of equipment used in the substation, stroke current I_{s0} should cause no damage to equipment.

12.4.6 Multiple Shielding Electrodes

The electrogeometric modeling concept of direct stroke protection has been demonstrated for a single shield mast. A typical substation, however, is much more complex. It may contain several voltage levels and may utilize a combination of shield wires and lightning masts in a three-dimensional arrangement. The above concept can be applied to multiple shielding masts, horizontal shield wires, or a combination of the two. Figure 12.14 shows this application considering four shield masts in a multiple shield mast arrangement. The arc of protection for stroke current I_s is shown for each set of masts. The dashed arcs represent those points at which a descending stepped leader for stroke current I_s will be attracted to one of the four masts. The protected zone between the masts is defined by an arc of radius S with the center

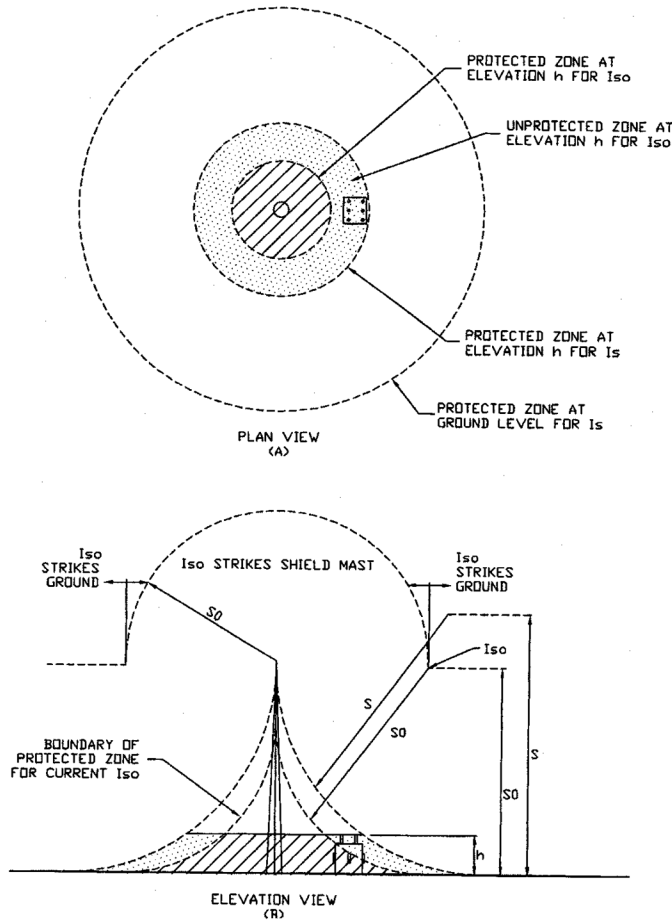


FIGURE 12.13 Shield mast protection for stroke current I_{s0} . (IEEE Std. 998-1996. With permission.)

at the intersection of the two dashed arcs. The protective zone can again be visualized as the surface of a sphere with radius S , which is rolled toward a mast until touching the mast, then rolled up and over the mast such that it would be supported by the masts. The dashed lines would be the locus of the center of the sphere as it is rolled across the substation surface. Using the concept of rolling a sphere of the proper radius, the protected area of an entire substation can be determined. This can be applied to any group of different height shield masts, shield wires, or a combination of the two. Figure 12.15 shows an application to a combination of masts and shield wires.

12.4.7 Changes in Voltage Level

Protection has been illustrated with the assumption of a single voltage level. Substations, however, have two or more voltage levels. The rolling sphere method is applied in the same manner in such cases, except that the sphere radius would increase or decrease appropriate to the change in voltage at a transformer. (Sample calculations for a substation with two voltage levels are given in annex B of IEEE Std. 998-1996.)

12.4.8 Minimum Stroke Current

The designer will find that shield spacing becomes quite close at voltages of 69 kV and below. It may be appropriate to select some minimum stroke current, perhaps 2 kA for shielding stations below 115 kV. Such an approach is justified by an examination of Figure 12.1 and Figure 12.2. It will be found that

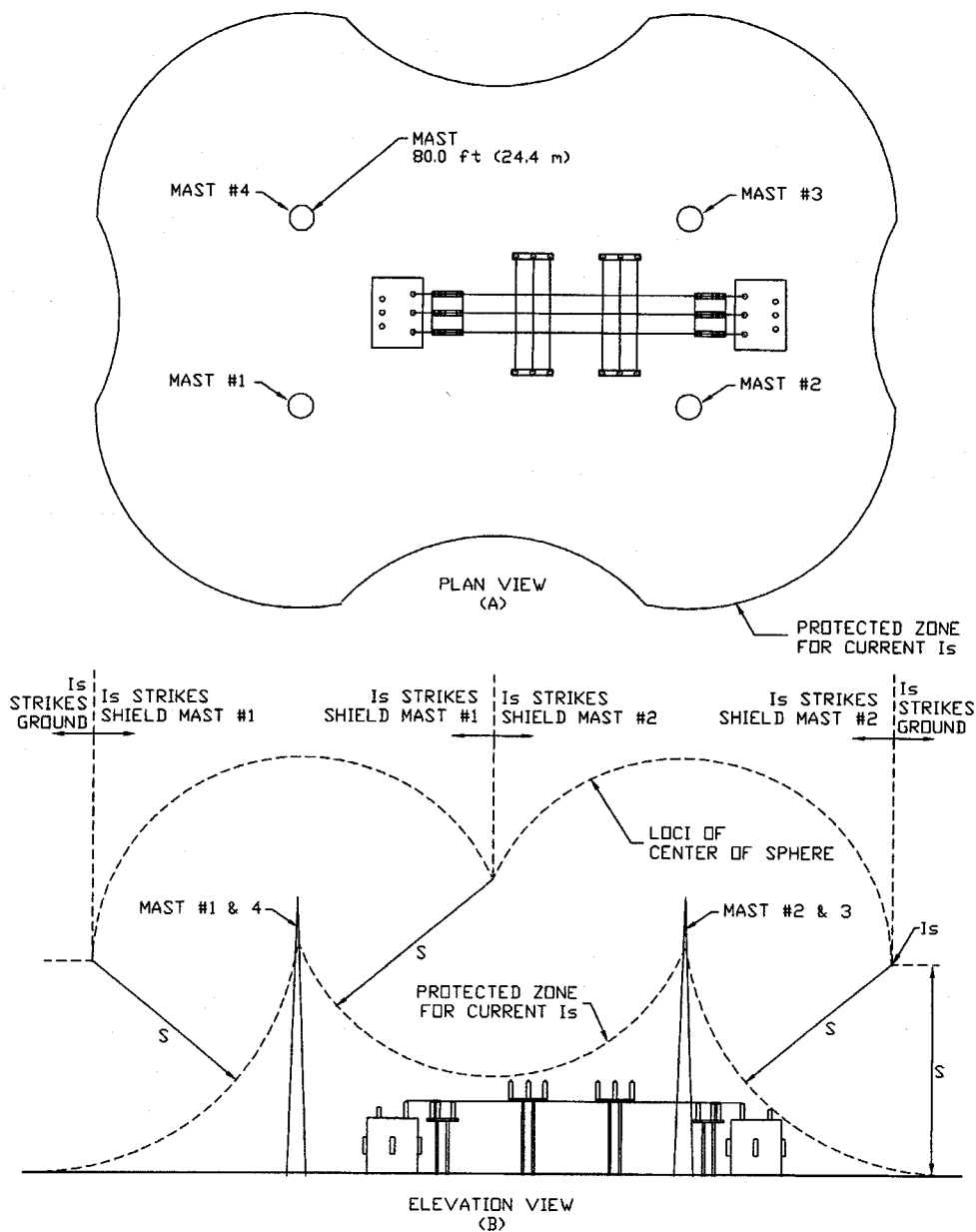


FIGURE 12.14 Multiple shield mast protection for stroke current I_s . (IEEE Std. 998-1996. With permission.)

99.8% of all strokes will exceed 2 kA. Therefore, this limit will result in very little exposure, but will make the shielding system more economical.

12.4.9 Application of Revised EGM by Mousa and Srivastava Method

The rolling sphere method has been used in the preceding paragraphs to illustrate application of the EGM. Mousa describes the application of the revised EGM (1976). Figure 12.16 depicts two shield wires, G1, and G2, providing shielding for three conductors, W1, W2, and W3. S_c is the critical striking distance as determined by Equation 12.11, but reduced by 10% to allow for the statistical distribution of strokes so as to preclude any failures. Arcs of radius S_c are drawn with centers at G1, G2, and W2 to determine

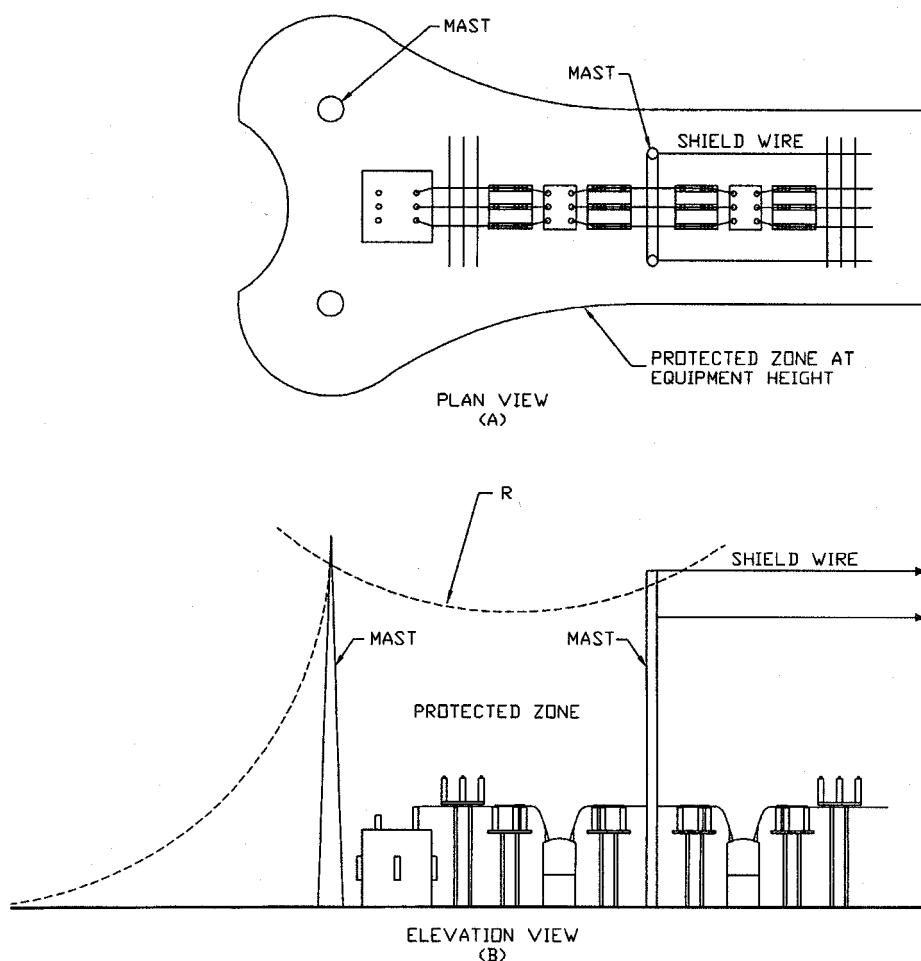


FIGURE 12.15 Protection by shield wires and masts. (IEEE Std. 998-1996. With permission.)

if the shield wires are positioned to properly shield the conductors. The factor ψ is the horizontal separation of the outer conductor and shield wire, and b is the distance of the shield wires above the conductors. Figure 12.17 illustrates the shielding provided by four masts. The height h_{mid} at the center of the area is the point of minimum shielding height for the arrangement. For further details in the application of the method, see Mousa (1976). At least two computer programs have been developed that assist in the design of a shielding system. One of these programs (Mousa, 1991) uses the revised EGM to compute the surge impedance, stroke current, and striking distance for a given arrangement of conductors and shield systems, then advises the user whether or not effective shielding is provided. (Sample calculations are provided in annex B of IEEE Std. 998-1996 to further illustrate the application.)

12.5 Calculation of Failure Probability

In the revised EGM just presented, striking distance is reduced by a factor of 10% so as to exclude all strokes from the protected area that could cause damage. In the empirical design approach, on the other hand, a small failure rate is permitted, typically 0.1%. Linck (1975) also developed a method to provide partial shielding using statistical methods. It should be pointed out that for the statistical approach to be valid, the size of the sample needs to be large. For power lines that extend over large distances, the total exposure area is large and the above criterion is met. It is questionable, therefore, whether the

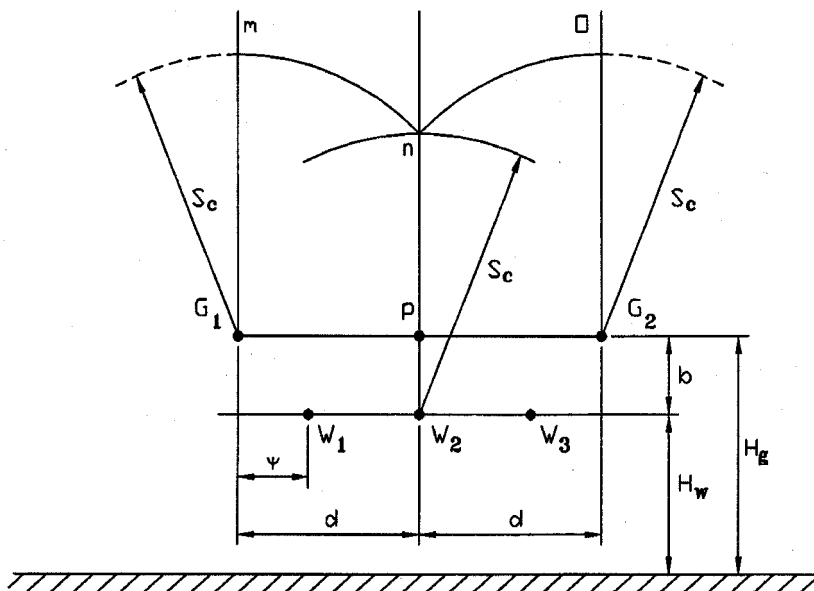


FIGURE 12.16 Shielding requirements regarding the strokes arriving between two shield wires. (IEEE Std. 998-1996. With permission.)

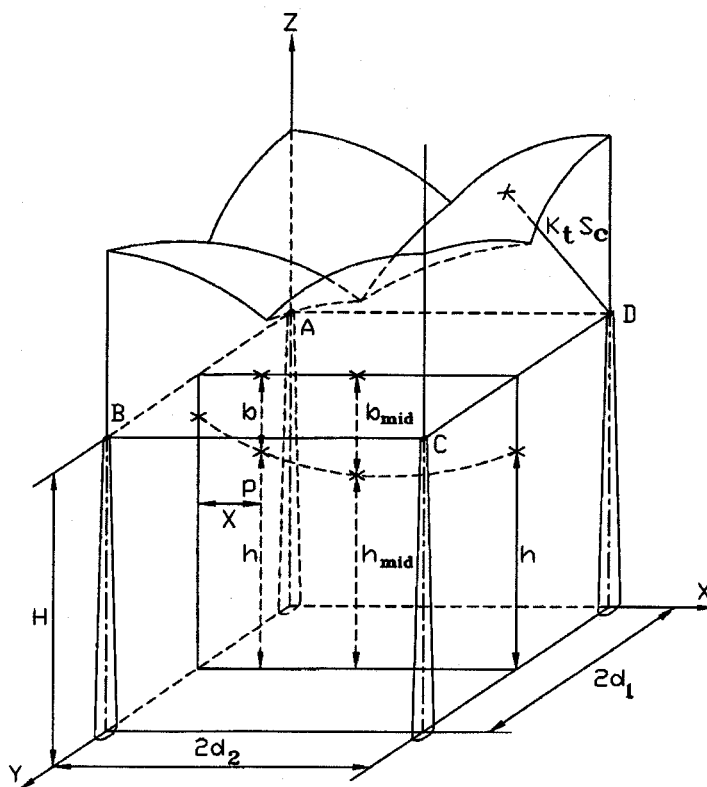


FIGURE 12.17 Shielding of an area bounded by four masts. (IEEE Std. 998-1996. With permission.)

statistical approach is as meaningful for substations that have very small exposure areas by comparison. Engineers do, however, design substation shielding that permits a small statistical failure rate. Orrell (1988) has developed a method of calculating failure rates for the EGM rolling sphere method. (This method is described with example calculations in annex D of IEEE Std. 998-1996.)

12.6 Active Lightning Terminals

In the preceding methods, the lightning terminal is considered to be a *passive* element that intercepts the stroke merely by virtue of its position with respect to the live bus or equipment. Suggestions have been made that lightning protection can be improved by using what may be called *active* lightning terminals. Three types of such devices have been proposed over the years:

- *Lightning rods with radioactive tips* (Golde, 1973). These devices are said to extend the attractive range of the tip through ionization of the air.
- *Early Streamer Emission (ESM) lightning rods* (Berger and Floret, 1991). These devices contain a triggering mechanism that sends high-voltage pulses to the tip of the rod whenever charged clouds appear over the site. This process is said to generate an upward streamer that extends the attractive range of the rod.
- *Lightning prevention devices*. These devices enhance the *point discharge* phenomenon by using an array of needles instead of the single tip of the standard lightning rod. It is said that the space charge generated by the many needles of the array neutralize part of the charge in an approaching cloud and prevent a return stroke to the device, effectively extending the protected area (Carpenter, 1976).

Some of the latter devices have been installed on facilities (usually communications towers) that have experienced severe lightning problems. The owners of these facilities have reported no further lightning problems in many cases.

There has not been sufficient scientific investigation to demonstrate that the above devices are effective; and since these systems are proprietary, detailed design information is not available. It is left to the design engineer to determine the validity of the claimed performance for such systems.

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